Moment-of-Fluid Interface Reconstruction

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Volume-of-fluid (VoF) methods are widely used in Eulerian simulations of multiphase flows with mutable interface topology. The strategy of VoF methods consists in calculating the interface location at each discrete moment of time from the volumes of the cell fractions occupied by different materials. Most VoF methods use a single linear interface to divide two materials in a mixed cell. Unfortunately the interface normal cannot be evaluated without the volume fraction data from the surrounding cells, which prohibits the resulting mass-conservative approximation to resolve any interface details smaller than a characteristic size of the cell cluster involved in evaluation of the normal.

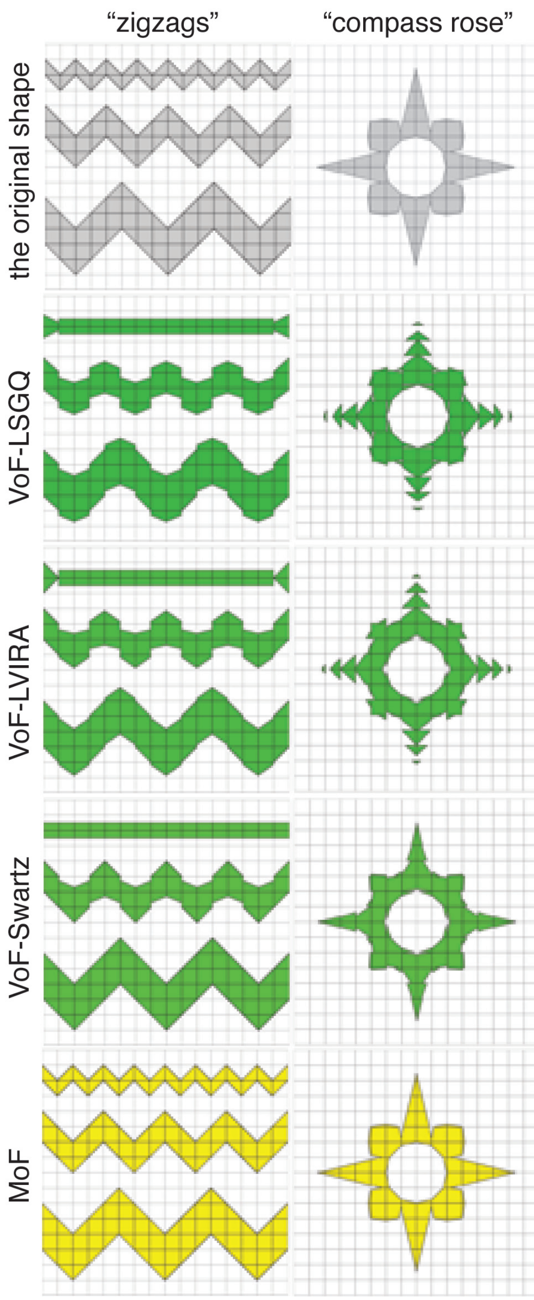

Fig. 1.
Examples of mass-conservative interface reconstruction with various algorithms. MoF algorithm demonstrates higher resolution than any of VoF counterparts.

In order to overcome this inherent limitation of VoF methods, we propose to enrich the interface reconstruction input data set with centroids of the cell fractions. The amount of information carried by the volumes and centroids or, equivalently, by the first two moments of the cell fractions is sufficient to define a mass-conservative piecewise-linear approximation even without exchanging the data between the cells. Subject to matching the prescribed volume exactly, the method minimizes the discrepancy between the centroid of the material behind the interface and the prescribed centroid. This strategy, called moment-of-fluid (MoF) interface reconstruction, results in unique, stable, second order accurate approximation; linear interfaces are reconstructed exactly.

With no data from the adjacent cells participating in evaluation of the interface, the new method is able to resolve the interface details as small as the cell itself, i.e., two to three times smaller than conventional VoF methods. Due to its autonomous nature, the MoF interface recontruction can be implemented as a cell-by-cell black box routine, which is a great technological advantage over the VoF, especially in 3-D.

Compared to alternative approaches, which exploit purely geometrical principles, the centroid data involvement has a clear mechanical reason. Each instance of an inexact interface reconstruction introduces some redistribution of the fluid inside a mixed cell. This fluid motion is unrelated to any physical force presented in a discrete model. Any displacement Δx of the fraction centroid caused by the interface reconstruction can be interpreted as an action of an artificial external force of magnitude ≈ $m\Delta x / \tau^2$ (here m is the mass of the fraction, and τ is the time increment). Therefore by complying with original centroids we explicitly reduce these artificial forces and improve the approximation properties of the discrete model of fluid dynamics.

By its design MoF algorithm results in the minimal defect $m\Delta x$ of the first moment attainable with a mass-conservative piecewise-linear approximation. In this sense MoF interface reconstruction is the optimal in the class of mass-conservative piecewise-linear methods.

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[1] V. Dyadechko and M. Shashkov, "Moment-of-Fluid Interface Reconstruction," Los Alamos National Laboratory report LA-UR-05-7571 (October 2005).

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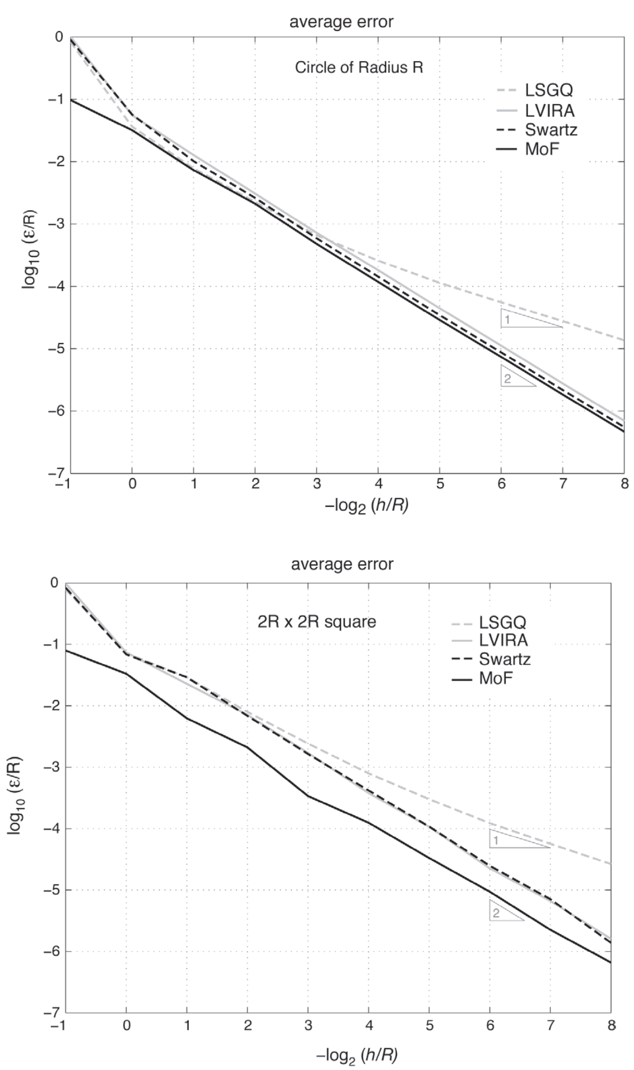

Fig. 2.
The graphs show how the interface reconstruction error ε (the average deviation of the reconstructed interface from the original one) scales with the mesh spacing h in case of the circular and square test shapes.